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13. ABSTRACT (Maximum 200 words)

Under ARO supports, we have advanced the following fundamental knowledge in the man-made quantum phenomena: observation of resonant tunneling via the nano-particles of silicon embedded in a silicon dioxide matrix; theoretical models of dielectric constant, doping, capacitance and excitons in Si nano-particle, and visible light emission from superlattices consisting of alternate layers of silicon with adsorbed oxygen forming an epitaxial Si/O superlattice. Moreover this superlattice represents a new kind under the name Semiconductor-Atomic-Superlattice (SAS). We have achieved several important breakthroughs: Si/O superlattice showing a 0.5eV barrier height; a nine-period system showing electroluminescence (EL) which has lasted for more than a year without degradation; and the continuation of silicon epitaxy beyond the adsorbed oxygen with low defect density arising from the monolayer of oxygen, being less than 10^9 /cm^2. The thin barrier is at most 1-2nm thick, which allows adjacent quantum states to couple strongly, forming an energy band.

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1. BRIEF OUTLINE OF RESEARCH FINDINGS AND ACCOMPLISHMENTS

Under the ARO supports, we have advanced a number of fundamental understandings in the world of man-made quantum phenomena, these includes:

- Quantum confinements in nanoscale silicon particles embedded in an oxide matrix and the observation of resonant tunneling via the nano-particles. The silicon nano-particles embedded in an amorphous oxide matrix were produced by annealing and/or oxidation of a thin (10-20nm) a-Si. Transport through this layer established tunneling through quantum states of the nano-particles.

- Theoretic models of dielectric constant, doping, capacitance and excitons in Si nano-particles.

- Visible Light emission in Si nanoparticles, both in Porous Si and in an oxide matrix.

- Epitaxial barrier in silicon: with multi layers of Si/adsorbed oxygen. Silicon epitaxy beyond the disordered monolayer of adsorbed oxygen has low defect density, being less than 10^9 $/cm^2$. This Si/O superlattice barrier forms the basis of silicon quantum devices. A 2-period structure shows an effective barrier height of 0.5eV, sufficient for most silicon quantum devices at room temperature. The structure may be used to replace silicon on insulator (SOI) for high speed, low power transistors of the future.

- An electroluminescent diode structure consisting of a 9 period of Si (1.1nm) / monolayer of adsorbed oxygen superlattice shows visible light with a peak at 2.2eV life-tested for more than one year without degradation.

- The time for thinking of an all silicon optoelectronic device is at hand-an electronic and photonic superchip.

4. Statement of the problem studied

Quantum mechanical devices utilize the wave nature of electrons for their operations whenever the electron mean-free-path exceeds the appropriate dimensions of the device structure. In the past several years, certain schemes appeared which may facilitate the realization of silicon quantum devices, such as the resonant tunneling via nanoscale silicon particles imbedded in an oxide matrix, and the superlattice barrier for silicon consisting of several period of Si/O. Our main finding for the observation of tunneling via quantum states represented by silicon nano-particles embedded in an oxide matrix is the use of a controlled forming process.

Epitaxially grown silicon beyond the superlattice barrier region, consisting of adsorbed oxygen is low in stacking fault defects, and thus is potentially important for silicon based quantum devices, including electroluminescent diodes, as well as serving as an SOI (silicon on

insulator).The replacement of SOI by the epitaxially grown Si/O superlattice barrier should promote the effort in high speed and low power MOSFET devices.

5. Summary (also see 1.)

Speed and density go together : scaling down the device size leads to higher speed and density. How far can scaling go? Operating voltages are set by the thermal voltage. Reducing size results ultimately to highfields beyond the breakdown. Besides, quantum effects will be reached at some point. These effects are not all desirable, for example, quantum interference is too size dependent, demanding unrealistic manufacturing tolerances. As the size approaches few nm, it is even impossible to dope due to the drastic increase in the binding energy of dopants. Classically, one talks about storing charges, as we have seen that quantum mechanically, one can only confine charges with a barrier. And electrons and holes confined in a barrier do leak out. Surely one can use thicker barrier to reduce tunneling, then, it is not possible to quickly remove the confined particle unless a large barrier lowering field is applied. The problem with this scheme is that one needs to localize the applied field, otherwise many adjacent structures will be affected. What is needed is judicious applications of quantum effects far from the notion that quantum transistors must be better! Fortunately, what is focussed in this report is not about wide spread utilization of quantum confinement. Rather, in some specific applications, for example,(a) the epitaxial Si/O superlattice for replacing the SOI fabricated by ion-implantation, (b) fabrication of a RTD in silicon, (c) increasing the oscillator strength of silicon by quantum confinement for optoelectronic purposes, and (d) discretizing the I-V as resonant tunneling via nanoscale particles for multistage logic and functional devices. After stating all that, I am impelled to be optimistic that a totally new system fully utilizing the wave nature of quantum mechanics is right around the corner, waiting to be explored, even in silicon. The task at hand is huge, therefore, it is important to sort out those goals which can be successfully pursued with the available funding, to arrive at some consensus among the researchers for future endeavors.

Although much of this report has been summarized in the publication, Room Temperature Silicon Quantum Devices, R. Tsu, in International J. High Speed Electronics and Systems, editors M. Dutta and M. Stroscio, **9**, (1), 145 (1998); I like to include three figures:

Fig.1 showing the high resolution TEM of the epitaxy beyond the O/Si/O/Si/O (whitish region),

Fig.2 showing a plane view-TEM Si/O with $10^8 - 10^9$ /cm^2 defect density, and

Fig.3 showing the electroluminescence of a 9-period Si(1.1nm)/O superlattice under the application of 10V reverse bias operating continuously for over one year.

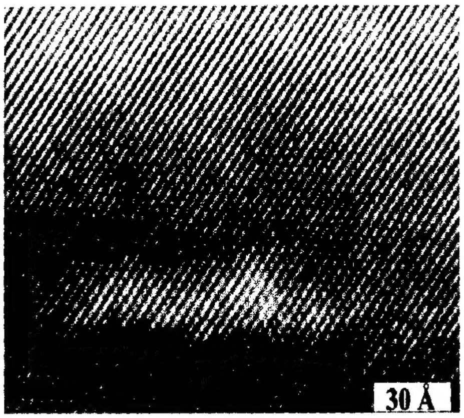

Fig.1 High Resolution showing the continuation of epitaxy beyond the O/Si/O/Si/O (white region)

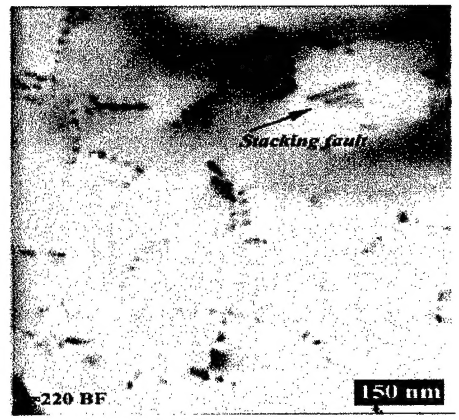

Fig.2 Plane View – TEM: Si/O (2.5nm) showing 10^9 / cm ^{2} defect density

Fig.3 Electroluminescence of a 9-period Si/O – superlattice. The green emission shows the active EL from 0.5 x 1.2mm thin partially transparent gold contact

It is commonly assumed that the Si/Ge superlattice system is the only quantum devices possible. I like to point out that the Si/Ge system restricts quantum confinement in the Ge. Therefore the Si/Ge system is a Ge system rather than a Si system! All the results reported here involve quantum confinement in silicon, therefore, silicon quantum devices are potentially possible with the Si/O superlattice system.

In conclusion, quantum devices involving silicon nanoparticles cannot be implemented yet because size control, which calls for much larger effort, has not been perfected. On the other hand, the Si epitaxy sandwiched between adsorbed species is demonstrated, which is ready for playing an important role in quantum devices, particularly, the optoelectronic devices.

6. Publications

The publication list important to this proposed study:

107. Optical Properties of Quantum Steps, H. Shen, F. H. Pollak and R. Tsu, Appl. Phys. Lett. 57, 13 (1990).

108. Some New Insights in the Physics of Quantum Well Devices, R. Tsu, SPIE 1361, 231 (1990).

109. Resonant Tunneling in Microcrystalline Si Quantum Box Diode, R. Tsu, Q. Y. Ye and E. H. Nicollian, SPIE 1361, 313 (1990).

112. Resonant Tunneling Via Microcrystalline Silicon Quantum Confinement, Q. Y. Ye, R. Tsu and E. H. Nicollian, Phys. Rev. B 44, 1806 (1991).

114. Correlation of Raman and Photoluminescence Spectra of Porous Silcon, R. Tsu, H. Shen and M. Dutta, Appl. Phys. Lett. 60, 112 (1992).

115. Microstructure of Visible Luminescent Porous Silicon, M. W. Cole, J. F. Harvey, R. A. Lux, D. W. Eckart and R. Tsu, Appl. Phys. Lett. 60, 2800 (1992).

122. Transport in Nanoscale Silicon Clusters, R. Tsu, Physica B 189 235 (1993).

124. Electrical Properties of a Silicon Quantum Dot Diode, E. H. Nicollian and R. Tsu, J. Appl. Phys. 74, 4020 (1993).

125. Silicon Quantum Well with Strain-Layer Barrier, R. Tsu, Nature 364, 19 (1993).

127 Physics of Extreme Quantum Confinement Exemplified by Si/SiO2 System, R. Tsu, in The Physics and Chemistry of SiO2 and the Si-SiO2 Interface 2, Eds. C.R.Helms and B.E. Deal (Plenum Press, Pub. 1993) p.353

131. Doping of a Quantum Dot, R. Tsu and D. Babic, Appl. Phys. Lett. 64, 1806 (1994).

133. Slow Conductance Oscillations in Nanoscale Clusters of Quantum Dots, R. Tsu, X. L. Li, and E. H. Nicollian, Appl. Phys. Lett. 65, 842 (1994).

140. Visible Light Emission in Silicon-Interface Adsorbed Gas Superlattices, R. Tsu, J. Morais, and A. Bowhill, Mat. Res. Soc. Symp. Proc. 358, 825 (1995).

141. Avalanche Amplification of Resonant Tunneling through Parallel Silicon Microcrystallites, Phys. Rev. B51, 13337,(1995)

144. Correlation of Raman and Optical studies with AFM in Porous Si,Adam A. Flilios, Susan

S. Hefner, and Raphael Tsu,J.Vac. Sci.& Tech.B14,3431(1996)

145 A Simple Model For The Dielectric Constant Of Nanoscale Silicon Particle, R. Tsu,D.Babic, and L.Ioriatti, J. Appl. Phys. 82, 1327(1997)

145. Exciton in Nanoscale Silicon Quantum Dots, D.Babic and R. Tsu, Superlattice and Microstructure, 22, 581(1997)

146 The Determination of Activation Energy in Quantum Wells, J. Ding and R. Tsu, Appl. Phys. Lett. 71, 2124 (1998)

148 Visible Electroluminescence in Si/absorbed Gas Superlattice, R. Tsu, Q.Zhang, and A.Filios, SPIE 3290, 246, (1998).

151 Silicon Epitaxy on Si(100) with Adsorbed Oxygen", R. Tsu, A.Filios, C.Lofgren, K.Dovidenko, and C.G.Wang, Electrochem. & Solid State Lett. 1, 80(1998).

152 Photovoltaic Effects", D. Boeringer and R. Tsu, in Encyclopedia of Electrical and Electronic Engineering, ed. J.G.Wester (John Wiley & Sons, NY 1998).

153 Room Temperature Silicon Quantum Devices, R. Tsu, in International J. High Speed Electronics And Systems, editors M. Dutta and M. Stroscio, **9**, (1), 145 (1998)

155 Perspectives of Light Emitters in Nanoscale Silicon, R. Tsu, 9th Cimtec-World Forum on New Materials, Symp.X-Innovative Light Emitting Materials,P. Vincenzini, G.C.Righini (Editor) Techna Srl,1999

7. List of Participants (Including those supported by previous ARO grant, also some of those listed were supported for only part of the grant period)

Postdoctoral fellows

Dr. Q. Zhang	Post-doctoral fellow, Jan.1998 – Dec.1998 (1/4)
Dr. Jinli Ding	Post-doctoral fellow, Jan.1998 - Mar. 1998(1/4), now at U. Toronto

Students

A. Filios	Ph.D., May 1999 (1/4), MS 1995
J.Dinkler	MS Fall 1998 (1/2)
F. de Freitas	MS candidate , April 1998 – Dec.1998 (1/4)
C. Lofgren	MS 1993, Ph.D. Candidate Joint NC-State/UNCC program

8. Reports of Inventions:

No Invention was disclosed under this contract on Proposal No. 36223-EL, DAAG55-97-1-0007, entitled : **Nanoscopic Studies of Quantum Effects in Silicon Quantum Dots** . However, prior to the funding of this proposed studies became finalized, this investigator was associated with the ETDL of the US Army Communications-Electronics Command, Fort Monmouth NJ 07703, via a GEO Contract DAAL01-89-C-0927, where he was involved with others on the following disclosures closely related to the proposed work.

- Patent filed 8/13/97, #08/915,547 , **Negative Differential Resistance Device Based on Tunneling Through Microclusters, and Therefor,** AMSEL-LG-L Fortmonmouth, NJ 07703-5000, by James F. Harvey, Robert A. Lux and Raphael Tsu. This disclosure deals with tunneling through resonant energy levels in microclusters to acieve NRD, and hence oscillator, amplifier, and mixer, devices, based on the crystallization and oxidation of silicon clusters forming Si particles embedded in an amorphous silicon dioxide matrix between contacts. This is precisely the research topic of this proposed studies.

- Patent issued , May 6, 1997, #5,627,386, **Silicon Nanostructure Light-Emitting Diode** , by James F. Harvey, Robert A. Lux and Raphael Tsu, with assignee : The United States of America as represented by the Secretary of the Army. This patent deals with means to fabricate nanometer silicon tips to breakdown the momentum conservation resulting in light emission, which is closely related to the electroluminescence devices reported in the interim report dated April 8, 1999.

Both were filed by Fort Monmouth, Administered by Judith E. Cleveland, paralegal Specialist.